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# Ceramic filled resin based 3-D printed X-band dual-mode bandpass filter with enhanced thermal handling capability

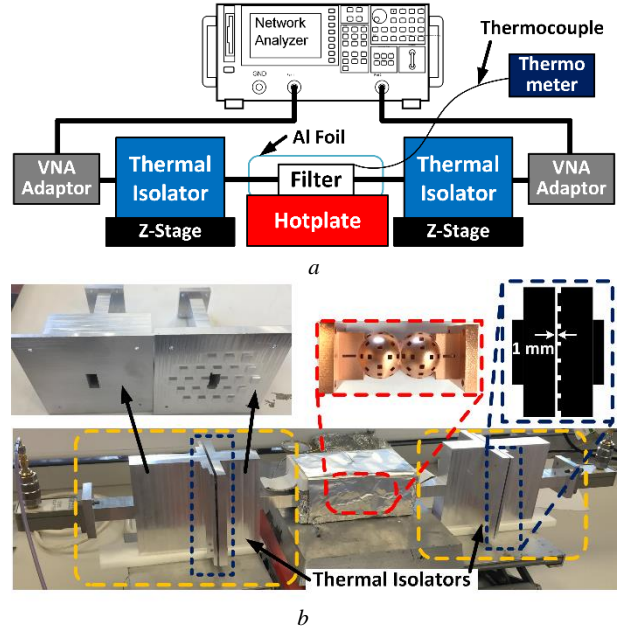
Cheng Guo, Jin Li, Duc D. Dinh, Xiaobang Shang, Michael J. Lancaster, and Jun Xu

This letter for the first time presents a miniaturized spherical resonator based X-band dual-mode bandpass filter that is 3-D printed using a ceramic filled photosensitive resin. This filter has substantially enhanced thermal handling capability than its counterparts that are printed out of the conventional resins with a relatively low working temperature. The filter's thermal handling capability is experimentally characterized by measuring its RF performance under different working temperatures using a pair of tailor made aluminium thermal isolators to separate the network analyser from the heat source. The measured results demonstrate that the ceramic resin based filter is capable of operating at much higher temperatures, and has a much better thermal stability than the one made of ordinary resin, without losing its intrinsic light-weight advantage over the one made of metal. This type of thermally-stable ceramic filled resin can be widely applied to stereolithography-based 3-D printed lightweight microwave and millimetre-wave waveguide devices.

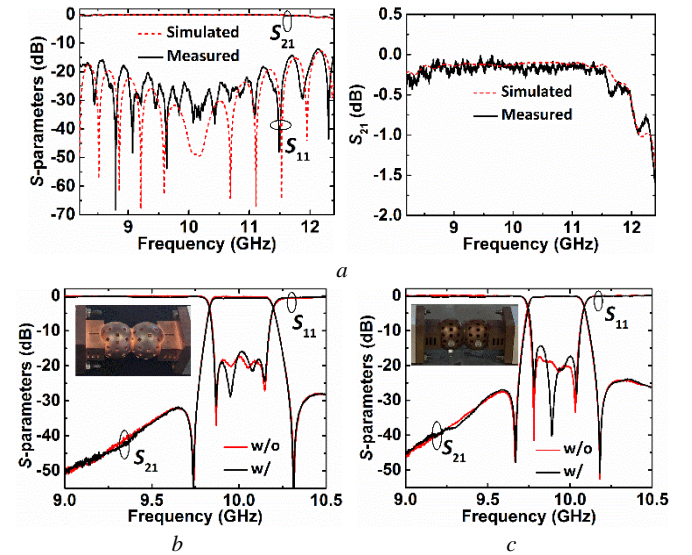
**Introduction:** Emerging 3-D printing technology provides cost efficient fabrication of geometrically complex microwave and millimetre-wave devices with high printing resolution, small surface roughness, as well as numerous durable printing materials with high mechanical strength and thermal handling capability. As one of the high-resolution 3-D printing techniques, stereolithography (SLA) has been applied to the fabrication of many millimetre-wave waveguide devices, such as rectangular waveguides and X- and W-band bandpass filters (BPFs) [1–4] demonstrating good RF performance. These devices are printed layer by layer using nonconductive photosensitive resins and employing an ultraviolet laser for defining the shape. This is followed by a surface metallization process. Such devices can feature a highly reduced weight due to the use of low density resin without compromising any of their attractive RF performance.

However, many conventional cured resins suffer from a poorer thermal handling capability than conventional metallic materials such as copper and aluminium, which limits applications of such SLA printed devices under high-power and high-temperature operational scenarios. For example, the filters in [2, 3] are printed using a resin based polymer Accura® Xtreme™ [5] with a suggested working temperature of no more than 50 °C. They are able to achieve desired filtering responses at room temperature, but applications in high-temperature environments are not possible. Metallic 3-D printing (e.g., [6]) can be a high-temperature solution, but its relatively poor surface roughness makes it difficult to achieve an insertion loss as low as solid metallic devices. Such structures are also much heavier. Thermal handling capability of resin based devices can be enhanced by employing ceramic filled resins with working temperatures of usually over 120 °C (e.g., Somos® PerForm [7]). In this letter, a ceramic filled resin based SLA printed X-band dual-mode BPF is described for the first time. Thermal handling capability of the 3-D printed filter is experimentally characterized. The experiment quantitatively demonstrates that the ceramic filter is capable of operating at much higher temperatures and has a much lower centre frequency shift ( $\Delta f$ ) with temperature than the one made of ordinary resin, while maintaining its light-weight advantage over the metallic one.

**Filter design, experiments and discussion:** Two X-band dual-mode BPFs with an identical physical structure and the same design specifications were tested. Each filter is composed of two iris coupled spherical dual-mode resonators, and is designed with a centre frequency of 10 GHz, a fractional bandwidth of 3%, a passband return loss of 20 dB, and two intrinsic transmission zeros at 9.7 and 10.3 GHz. One filter (Filter A) was SLA printed using an ordinary resin (Accura Xtreme) and has previously been described in [3]. The other (Filter B) was SLA printed using a ceramic filled resin (Somos PerForm). The same surface metallization process (i.e., electroless plated nickel as a seed layer followed by electroplated 10  $\mu$ m thick copper) was adopted for both filters.

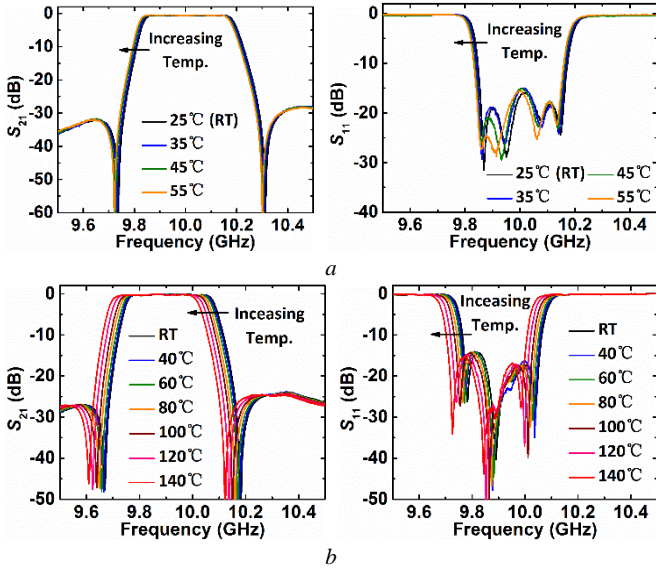


**Fig. 1** Measurement setup for thermal handling capability of the BPFs  
a Schematic diagram  
b Photograph

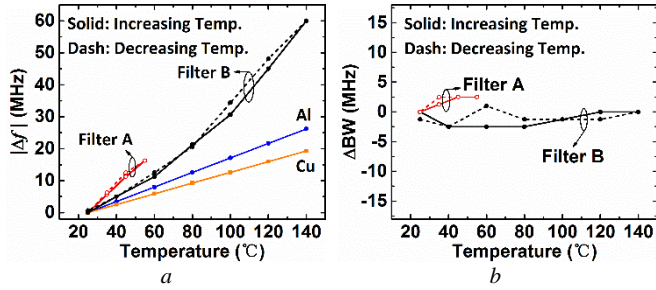


**Fig. 2** RF performance of the devices  
a S-parameters of the pair of back-to-back thermal isolators  
b Measured S-parameters of the filter A (Accura Xtreme)  
c Measured S-parameters of the filter B (Somos PerForm)

A schematic diagram and the photograph of the experimental setup are illustrated in Fig. 1. The filter under test is placed on a hot plate, and is series cascaded with a pair of tailor made aluminium thermal isolators in a back-to-back configuration. The thermal isolator was specially designed to separate the network analyser from the heat source so good control of the temperature is possible [8]. Each thermal isolator is composed of two sections of X-band rectangular waveguide that are separated by a 1 mm air gap so the heat can be isolated. To prevent radiation from the gap, a periodic bandgap structure [9] is placed between two waveguide flanges. The RF performance of the pair of back-to-back thermal isolators is plotted in Fig. 2a, showing a good agreement between the simulated and measured results. For this back-to-back configuration between 9 and 11 GHz, the thermal isolator pair contributes an insertion loss of 0.2–0.25 dB and a return loss better than 20 dB. Measured passband responses of the filter before and after the pair of thermal isolators were cascaded are compared in Fig. 2b and 2c. As expected, little influence is contributed by the thermal isolators to the filter's passband except for a small increase in passband insertion loss of around 0.25 dB. For filter B, the measured passband return loss



**Fig. 3** Measured  $S$ -parameters of the BPFs versus increased temperatures (RT: room temperature)  
a Filter A (Accura Xtreme):  $S_{21}$  (left) and  $S_{11}$  (right)  
b Filter B (Somos PerForm):  $S_{21}$  (left) and  $S_{11}$  (right)



**Fig. 4** Extracted filters' specifications versus temperatures  
a  $\Delta f$  (Assuming a constant  $\alpha$  of  $23.1 \times 10^{-6}$  and  $17 \times 10^{-6}$  /K for aluminium and copper, respectively).  
b  $\Delta BW$

was worse than the simulated one, and in order to compensate it, post tuning [3] was conducted. This compensation, however, contributes to a small filter centre frequency ( $f_0$ ) offset away from 10 GHz.

The filters' passband responses were measured using an HP8722ES network analyser under different temperatures in a ramp-up and ramp-down cycle. During this test, the filter was sheltered in a box with an aluminium cover for heat preservation. Inserted into the box, a Comark KM45 thermometer was connected to the filter using a thermocouple to monitor the filter's real-time temperature. The test temperature was raised up to 55 °C at intervals of 10 °C for filter A, and up to 140 °C at intervals of 20 °C for filter B. Note that for each filter under test, the highest test temperature was carefully controlled [5, 7] so that during the test no visible damage was observed in the filters. The filters'  $S$ -parameters were measured at each test temperature after a stabilization period of 30–40 minutes, and the corresponding results are plotted in Fig. 3. As can be seen, for both filters, good passband responses are maintained within their whole test temperature range, demonstrating an excellent heat resistance for filter B. An increased temperature results in a reduced centre frequency for both filters, which is due to an increased volume of the air cavity in each spherical resonator as a result of thermal expansion. However, the temperature variation has very little contribution to either of the filters' passband insertion loss or bandwidth.

A further quantitative investigation for both RF and material properties of the two filters can be conducted by extracting the filters'  $\Delta f$  and bandwidth variation ( $\Delta BW$ ) versus temperature, with the corresponding results plotted in Fig. 4. Using room temperature (25 °C) as the reference, the  $\Delta f$  from room temperature can be calculated using

$$\Delta f = f_0 \times \alpha \times \Delta T \quad (1)$$

where  $\alpha$  and  $\Delta T$  are the coefficient of thermal expansion of the material and the temperature difference from the room temperature. In the temperature range of 25–60 °C, the average rate  $\Delta f/\Delta T$  for the filter B is 0.32 MHz/°C, around 40% less than that (0.54 MHz/°C) for the filter A.

In the same range, the calculated rates for aluminium and copper are around 0.23 and 0.17 MHz/°C, respectively. The slight difference on the measured ramp-up and ramp-down curves in Fig. 4a maybe due to the viscoelasticity and viscoplasticity of the resins [10]. The  $\Delta BW$  for both filters is less than 2.5 MHz (<1%) in the entire test temperature range, as shown in Fig. 4b. This ceramic filled resin has a density of 1.61 g/cm<sup>3</sup> (at 25 °C), slightly higher than that of Accura Xtreme (1.19 g/cm<sup>3</sup>), but much smaller than that of aluminium (2.7 g/cm<sup>3</sup>) and copper (8.96 g/cm<sup>3</sup>). The results show the great potential of this material in applications of lightweight 3-D printed microwave and millimetre-wave waveguide devices. Furthermore, this type of ceramic filled resin is superior in its mechanical strength over that of the ordinary resin [5, 7], which indicates a better durability of this material than the latter for harsh environment applications.

**Conclusion:** A ceramic filled resin based 3-D printed X-band dual-mode BPF has been demonstrated with an enhanced thermal handling capability. This filter is capable of operating at much higher temperatures as well as exhibiting a much better mechanical strength and around a 40% lower frequency shift with temperature (25–60 °C) than the one made of ordinary resin. This is without compromising its intrinsic feature of a low density. This ceramic filled resin can be widely applied to the fabrication of other 3-D printed microwave devices.

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